SUPERSONIC LAMINAR FLOW CONTROL RESEARCH

FINAL REPORT
January 1994 - June 1996

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Technical Objectives

The objective of this research is to understand supersonic laminar flow stability, transition and active control. Some prediction techniques will be developed or modified to analyze laminar flow stability. The effects of distributed heating and cooling as an active boundary layer control technique will be studied. The primary tasks of the research apply to the NASA/Ames PoC and LFSWT's nozzle design with laminar flow control and are listed as follows:

1. Predictions of supersonic laminar boundary layer stability and transition,

2. Effects of wall heating and cooling on supersonic laminar flow control on a flat plate,

3. Performance evaluation of the PoC and LFSWT nozzle designs with wall heating and cooling applied at different locations and various lengths,

4. Effects of a conducted -vs- pulse wall temperature distribution for the LFSWT and,

5. Application of wall heating and/or cooling to laminar boundary layer and flow separation control of airfoils and investigation of related active control techniques.

Accomplishments of the First 24 Months (Refs. 1,2,3 & 4)

A. Prediction of Supersonic Laminar Boundary Layer and Stability

Two Computational Fluid Dynamics (CFD) codes which were used to conduct this study have been checked out successfully in the first half year. The first code is a boundary layer code developed by Harris at NASA (Ref. 5). This program solves the laminar, transitional, or turbulent compressible boundary layer equations for two dimensional or axisymmetric flows. The output of this code is used as input for the second CFD code developed by NASA contractor Malik (Ref. 6). This second program utilizes the compressible linear stability theory to predict the stability characteristics and the transition location of the boundary layer.

B. Temperature effects on the Stability of the Laminar Boundary Layer of a Flat Plate

The temperature effects on the stability of the laminar boundary layer was analyzed for a flat plate at M=1.6. The wall heating was applied to the leading ten percent of the flat plate and the rest of the plate remained at the adiabatic wall temperature. Three heating cases and an adiabatic case with wall temperatures 602°R, 702°R, 902°R and 502°R respectively were input into the boundary layer code. Each heating case increases the stability of the boundary layer with the N-factor getting smaller as the heating temperature increases. Details are reported in the Semi-Annual Report #1 (Ref. 1) as well as Lafrance's thesis (Ref. 7). These findings are consistent with theoretical results obtained for the subsonic flow in Ref 7.

C. Results for the PoC Nozzle with Local Strip Heating

Since the local strip heating can enhance the stability on the flat plate (i.e., without pressure gradient), it is reasonable to expect the same concept to apply to a nozzle configuration (i.e., with pressure gradient along the wall) in order to enhance the stability of the wall boundary layer.

One typical case is given here to illustrate the feasibility of searching for the optimal locations and increments of temperature for wall heating. Local heating and cooling strips are applied, in turn, at $2.86 \leq X \leq 3.73$ downstream of the nozzle entrance (station X=0.0) at 600°R and 400°R respectively. The total length of the NASA PoC nozzle and test section from the nozzle entrance to the test section exit is 9.23 units. Results obtained from both the curvature criterion and N-factor theory are consistent with the conclusion that the heating strip stabilizes the boundary layer. Details of these results and other cases are given in Section 2.3 and 3.3 of Meredith's master thesis (Ref. 9).

D. Stability and Transition Prediction for the Laminar Flow Supersonic Wind Tunnel (LFSWT)

The Laminar Flow Supersonic Wind Tunnel (LFSWT) is 5.05 feet long, including the nozzle and test section. Five strip locations were used to investigate the effects of local heating and cooling on the laminar boundary layer stability; three upstream of the instability on-set (I.O.) point and two downstream of the same. Since removal of heat energy from the flow enhances the boundary layer stability, the location of the heating/cooling strips relative to the I.O. point is critical. To enhance the stability, in general, a heating strip should be applied upstream on the I.O. point or a cooling strip downstream of the same. Furthermore, application of two strips on the wall; a heating strip upstream of the I.O. point and a cooling strip downstream of the same, is expected to increase the stability (decrease the N-factor) over that of the single strip configuration. All results are given in Ref. 10.

The current findings indicate that stability is enhanced by localized heating upstream of the I.O. point and/or cooling downstream of the I.O. point. Localized cooling downstream of the I.O. point is more effective in stabilizing the laminar boundary layer than is heating upstream of the I.O. point.

Localized heating far upstream of the I.O. point introduces heat energy into the flow which creates a positive temperature gradient directed out into the flow stream normal to the wall. Since the wall temperature downstream is lower than that of the boundary layer stream, the thermal energy in the boundary layer flows into the wall. As a result, a cooling effect is established near the wall in the vicinity of the I.O. point. This cooling of the boundary layer enhances the boundary layer stability. When local cooling is employed upstream of the I.O. point, the stability is reduced since a heating effect is produced near the wall in the vicinity of the I.O. point. However, stability is increased when localized cooling is applied downstream of the I.O. point. The theoretical study by Masad & Nayfeh (Ref.8) and experimental evidence obtained by Demetriades (Ref.11) of laminar boundary layer control for a subsonic flat plate and supersonic nozzle respectively, provide similar trends to those described above. The application of strip heating and/or cooling to the quiet tunnel's wall seems feasible, especially since the heating and/or cooling is localized and limited to certain upstream and downstream regions of the wall.

E. Stability and Transition Prediction with Conducted -vs- Pulse Wall Temperature Distribution for the LFSWT

The work done by Lo, et al. (Ref.10) on laminar boundary layer control for quiet supersonic wind tunnels employed heating and/or cooling strips to alter the adiabatic wall temperature distribution. In the above work, the local wall temperature distributions created by the heating/cooling strips were modeled as pulse functions, $T_w(x)$, of constant temperature and widths equal to the respective heating/cooling strip lengths.

It is important to refine the model of the local wall temperature distribution to a realistic, "conducted", wall temperature distribution. The conducted wall temperature distribution was achieved by modeling the wind tunnel wall as a semi-infinite plane with one-dimensional heat transfer parallel to the wall, and the heating/cooling strips characterized as point sources of thermal energy (Ref. 13). The effect of the "conducted" wall temperature distributions on the boundary layer stability were then studied and compared to the results of the pulse temperature distributions of Ref 10. Four cases were examined; two with heating/cooling strips upstream of the instability on-set (I.O.) point and two with the strips downstream of the same. The conducted wall temperature distributions used are considered reasonable, but not necessarily exact. The optimal overall conducted wall temperature distribution is sought for as the guideline for the quiet supersonic wind tunnel experiment.

The N-factor that results from the adiabatic wall temperature case provides the baseline to which all subsequent heating/cooling cases are compared. Cases with N-factors less than the baseline N-factor (N_b) stabilize the boundary layer, whereas those with N-factors greater than N_b de-stabilize the boundary layer. The results were examined by comparing the maximum N-factors and the I.O. locations for four cases (same as Case I,II,IV and V of Ref. 10).

The results revealed that the effects of a conducted wall temperature distribution, imposed by heating or cooling strips, on the boundary layer stability follow the same trend shown in Ref. 10 for a pulse temperature distribution. However, it was shown that for heating upstream of the I.O. point, the conducted temperature distribution produces more stable (lower N-factors) results than do the corresponding pulse temperature distributions. The same is true for cooling downstream of the I.O. point, except for Case IV where the I.O. point is delayed significantly, but after which the N-factor rises sharply. In both heating upstream or cooling downstream of the I.O. point, if the imposed temperature distribution extends over the adiabatic I.O. point, significant shifts in the I.O. point can occur along with increased uncertainty.

A conducted wall temperature distribution produces increased boundary layer stability compared to a pulse temperature distribution if properly placed relative to the I.O. point. Greater care must be taken in the placement of the heating /cooling strips relative to the I.O. point since the conducted temperature distribution influences more flow area. This work will be beneficial to the optimization of the heating/cooling locations.

Status of Progress

A. Application of Wall Surface Temperature Distribution to Drag Reduction of Airfoils and Dynamic Stall Control

Since reducing drag and increasing lift are the primary goals of applied aerodynamics, considerable effort is focused on developing techniques to delay both boundary layer transition (or laminar flow control) and flow separation of airfoils. In recent years, the application of boundary layer control has been divided into the two main areas of low drag and high lift. The key elements of these categories are transition delay and separation control; the former lowering friction drag and the latter lowering pressure drag and increasing lift. It is recognized, however, that a wall surface temperature distribution implemented to control the laminar boundary layer, that is delay transition, does not necessarily control flow separation. It has been shown that localized surface heating, appropriately applied, can delay transition under one configuration and control flow separation under another (Ref. 14).

In an effort to reduce drag and increase lift about airfoils, considerable attention has been given to active control of the laminar boundary layer and flow separation. Studies have shown that modifying the surface temperature condition, particularly with surface heating in a localized region of the airfoil surface, can have a significant effect on laminar boundary layer stability or separation control depending on how and where the heating is applied. Control of the laminar boundary layer by surface temperature distribution should not be confused with separation control by surface temperature distribution. Here laminar boundary control requires a surface, or longitudinal, temperature distribution, while separation control utilizes the local coupling between surface temperature and the separated shear layer. It is hoped, however, that an optimum surface temperature distribution can be found that delays transition and indirectly has a controlling effect on flow separation.

Previous work has shown the success of surface temperature distribution in controlling the laminar boundary layer, thus delaying transition, of the LFSWT (Refs. 1-4,9,10 & 12). Considering these results, it seems reasonable to expect successful laminar boundary layer control when surface heating and/or cooling is applied to airfoils.

The effect of surface temperature distribution on flow separation is analyzed using results from the Harris boundary layer code (Ref. 5). The model being used is the upper surface of a NACA 0012 airfoil at zero angle of attack and freestream Mach number of 0.6. The baseline case, which is the adiabatic surface configuration, results in a flow separation point at 45% chord. The velocity profiles and velocity slope profiles for this case at various stations along the airfoil are shown in Figures 1(a) and 1(b). Several trial cases with distributed wall temperature were performed, with the optimum of these cases resulting in a delay of flow separation to 69% chord. In this case, heating from 5% to 10% chord at a temperature of 640°R (approx. 1.2 times the average adiabatic wall temperature) is applied. Corresponding velocity profiles for this case are presented in Figures 2(a) and 2(b). Variations of this pseudo-optimum case are run to examine how the flow separation point would change in response to temperature deviations from the previously imposed 640°R. The results shown in the table below reveal that the flow separation point is vary sensitive to temperature variations. However, the reliability of these data is suspect when one considers the significant change in flow separation point as the temperature is changed by only ± 1 degree. These results were very surprising and, for now, are attributed to the sensitivity of the numerical solvers of the boundary layer code. For large temperature variations, on the order of 100 degrees, significant change in separation point was expected, which the tabular data confirms. The analysis, therefore only provides a qualitative trend from which to move forward and not quantitative conclusions.

It appears that surface heating can significantly alter the flow separation point, however much analysis needs yet to be performed to understand the effect of localized heating on flow separation. It is desired to find a temperature distribution that will optimize the stability of the boundary layer and delay separation. The effect of the above surface heating on the laminar boundary layer stability has not as yet been determined.

B. Investigation of Laminar Flow Control by Suction/Blowing and Induced Jets

At present a literature search has been performed on additional active flow control methods including suction/blowing and turbulent jets. The latter is of particular interest in which the excitation of turbulence is induced by surface actuators such as piezoelectric devices or other Microfabricated Electro-Mechanical Systems (MEMS). A round submerged turbulent water jet, shown in Figure 3(a), is produced normal to, and at the center of a rapidly oscillating thin metal disk flush-mounted about its perimeter on a submerged flat plate. The metal disk is part of a resonantly-driven actuator where the active element is a piezoelectric disk. The jet is formed without any mass injection across the actuator surface and thus is comprised entirely of entrained surrounding fluid (Ref.15). A simple test set-up schematic is shown in Figures 3(b) and 3(c).

The following examples of current research illustrate the impact of MEMS technology on sensors, actuators and controllers used on such active flow control problems as active control of free jets, boundary layer control and the control of aerodynamic forces on delta wings to mention a few. The microscale synthetic jet actuator, microfabricated by D. Coe and M. Allen, and corresponding jet are shown in Figure 4. The Jacobson actuator concept employing a resonant cantilever beam is shown in Figure 5. Finally, Figure 6 illustrates the implementation of MEMS actuators near the point of flow separation on the leading edge of a delta wing in an effort to modify the location and strength of the vorticity flux. The MEMS actuators are a line of microfabricated magnetic flaps on the undersurface near the leading edge (Ref. 16).

Publications Resulting From This Research:

Lafrance, R., "Stability Study of Laminar Boundary Layers with Wall Temperature Effects using Numerical Methods," Master Thesis, University of Tennessee, Knoxville, July 1994.

Meredith, William S., "Effect of Heating and Cooling Strips on Boundary Layer Stability of Nozzles and Test Sections of Supersonic Wind Tunnels," Master Thesis, University of Tennessee, Knoxville, December 1994.

Lo, C. F., Lafrance, R., Meredith, W. S., and Wiberg, C. G., "Laminar Flow Control with Wall Temperature Distribution for Quiet Supersonic Wind Tunnels," AIAA Paper 95-2296, Jun. 1995.

Lo, C.F., Lafrance, R., Meredith, W.S. and King, L.S., "Wall Temperature Effects on the Stability of Laminar Boundary Layers," Journal of Aircraft, Vol. 32, No. 5, Sept.-Oct., 1995, pp. 1162-1164.

Lo, C.F., "Supersonic Laminar Boundary Layer Control," NASA Group Meeting Paper, 3rd Orbiter Transition Working Group Meeting, Houston, TX, Nov. 8-9, 1995.

Recommendations:

- Apply the Neural Network Analysis to find heating/cooling strip configurations that will optimize the boundary layer stability and delay transition.
- Continue study of the effect of localized heating on flow separation control in an effort to find the optimum heating configuration for separation and boundary layer control.

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10. Lo, C. F., Lafrance, R., Meredith, W. S., and Wiberg, C. G., "Laminar Flow Control with Wall Temperature Distribution for Quiet Supersonic Wind Tunnels," AIAA Paper 95-2296, Jun. 1995.

11. Demetriades, A., "Stabilization of a Nozzle Boundary Layer by Surface Heating," AIAA 94-2501, June 1994.

12. Lo, C.F., Lafrance, R., Meredith, W.S. and King, L.S., "Wall Temperature Effects on the Stability of Laminar Boundary Layers," Journal of Aircraft, Vol. 32, No. 5, Sept.-Oct., 1995, pp. 1162-1164.

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Table: Flow Separation -vs- Temperature Variation

Surface Heating: 5% to 10% Chord Pseudo-Optimum: Temperature=640°R, Separation Point (SP)=69%	
Temperature Change (°R)	Separation Point (% Chord)
+1°R (641°R)	50%
+5°R (645°R)	48%
+10°R (650°R)	46%
+100°R (740°R)	45%
-1°R (639°R)	56%
-5°R (635°R)	48%
-10°R (630°R)	59%
-200°R (440°R)	50%

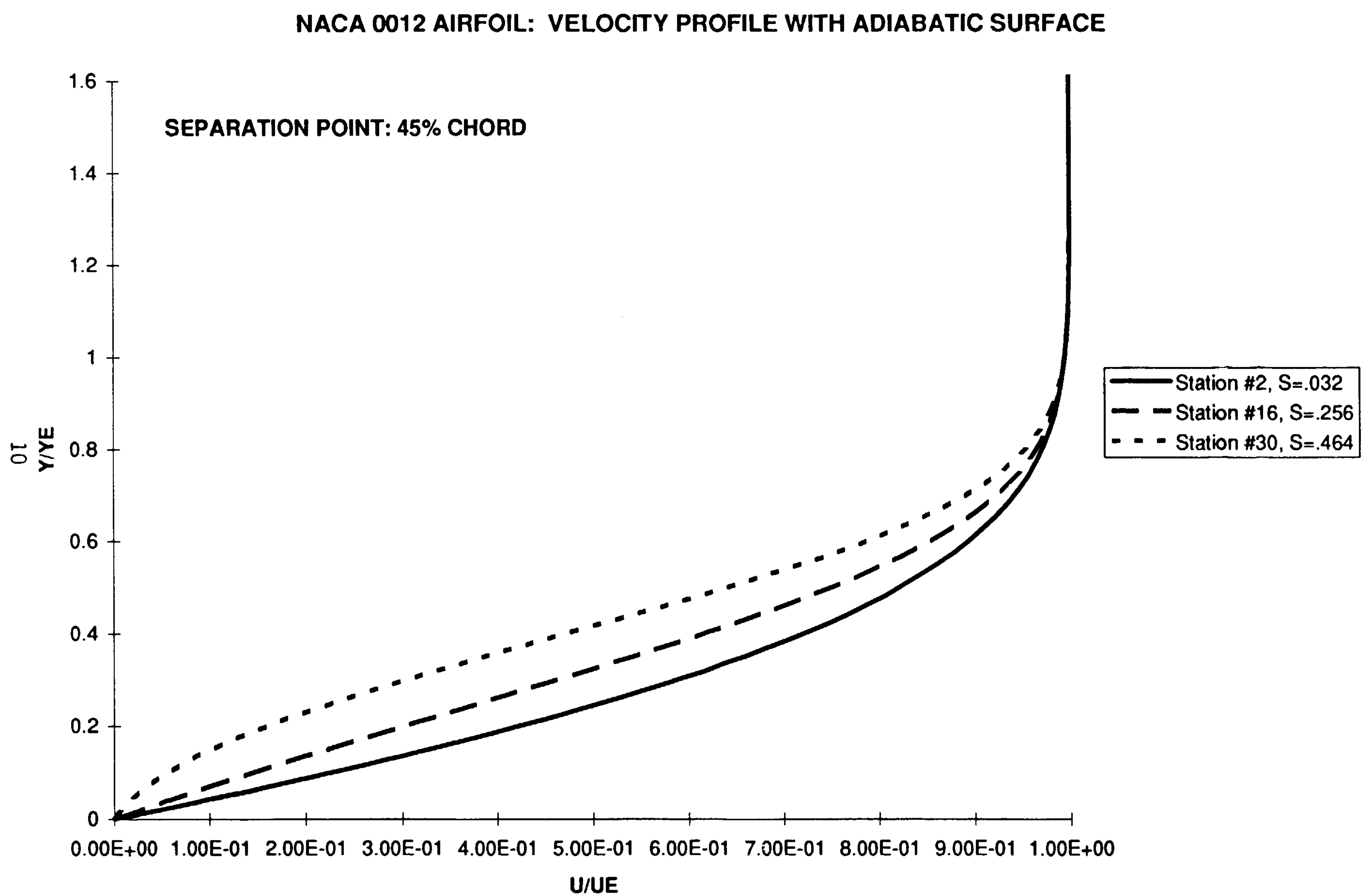


Figure 1 (a). Normalized velocity profile for adiabatic surface on the NACA 0012 airfoil.

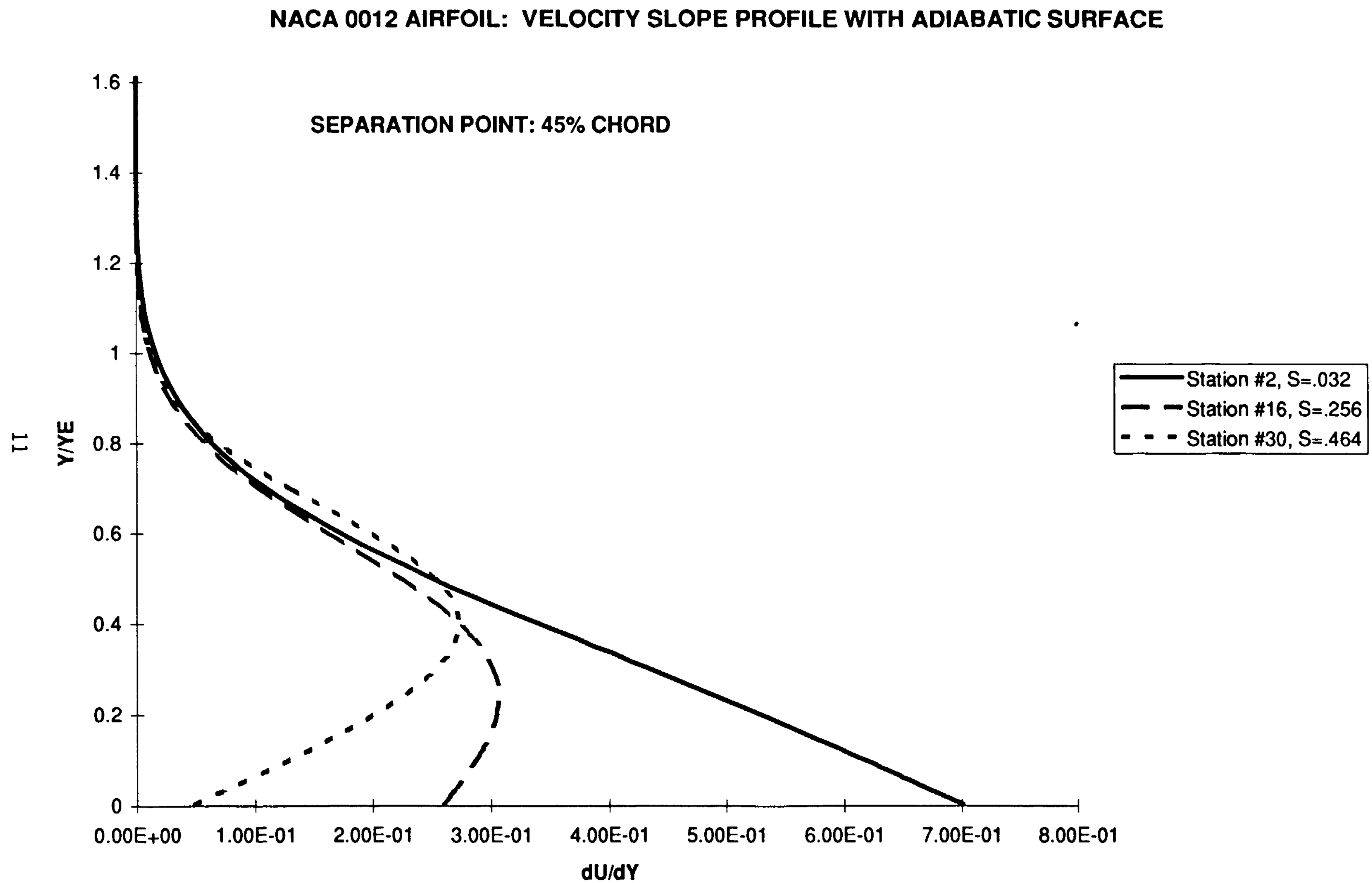


Figure 1 (b). Velocity slope profile for adiabatic surface on the NACA 0012 airfoil.

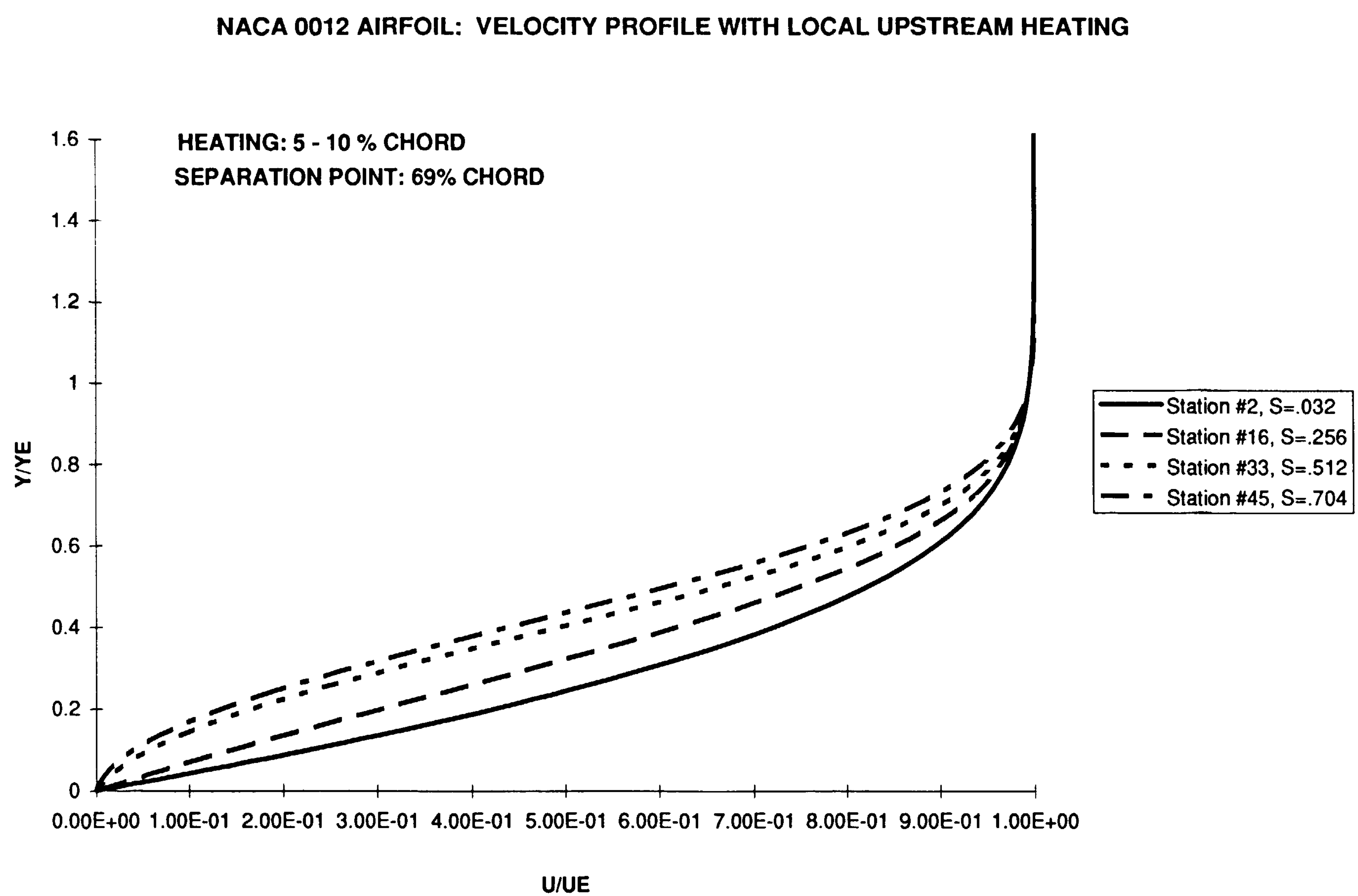


Figure 2 (a). Normalized velocity profile with heating at 5% - 10% chord on the NACA 0012 airfoil.

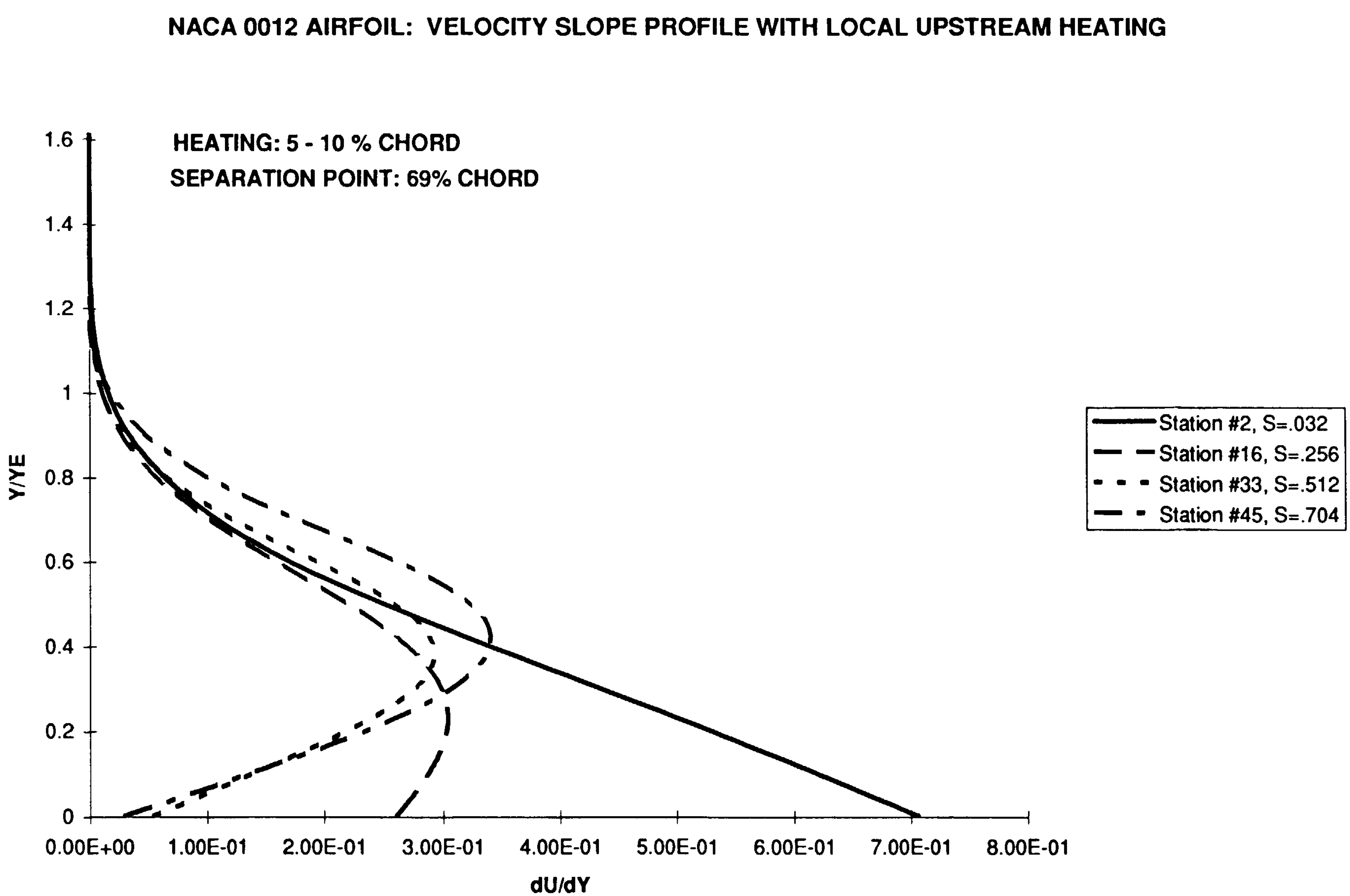
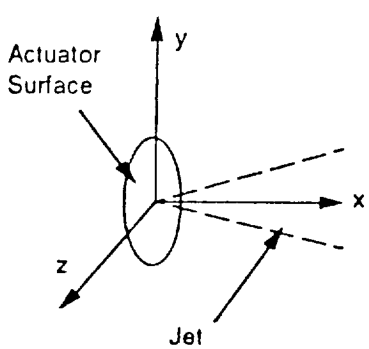
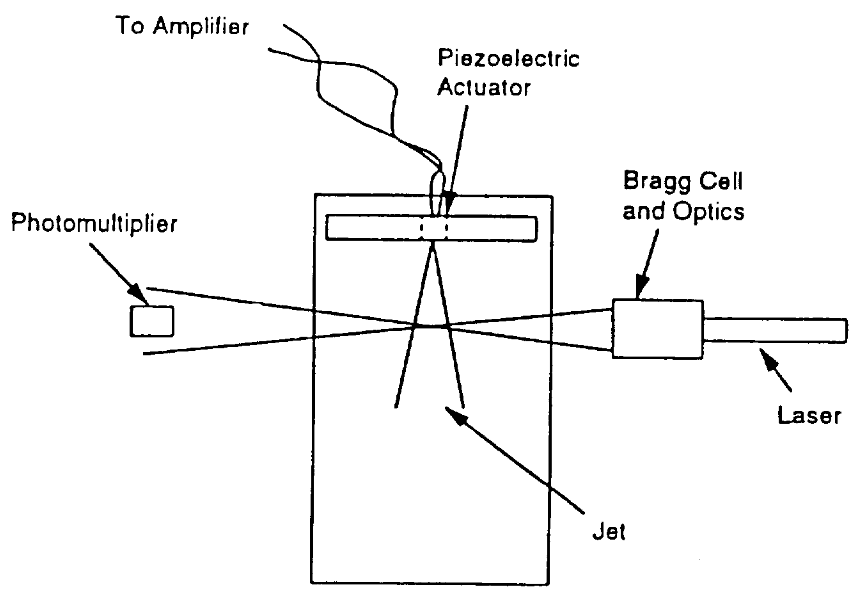


Figure 2 (b). Velocity slope profile with heating at 5% - 10% chord on the NACA 0012 airfoil.

(a)

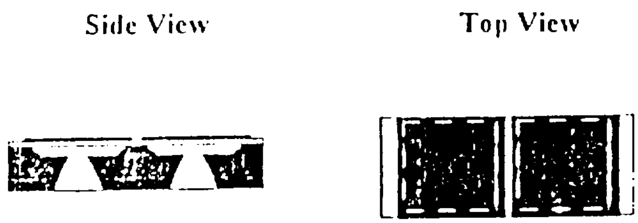


(b)



(c)

Figure 3. Submerged round turbulent water jet produced by a resonantly-driven piezoelectric actuator: (a) Dye visualization of surface jet, (b) Jet is formed normal to actuator surface and (c) The experimental set-up.



(a)

(b)

Figure 4. Microscale synthetic jet actuator microfabricated by D. Coe and M. Allen, Georgia Tech: (a) Microscale synthetic jet, (b) Smoke visualization of microjet.

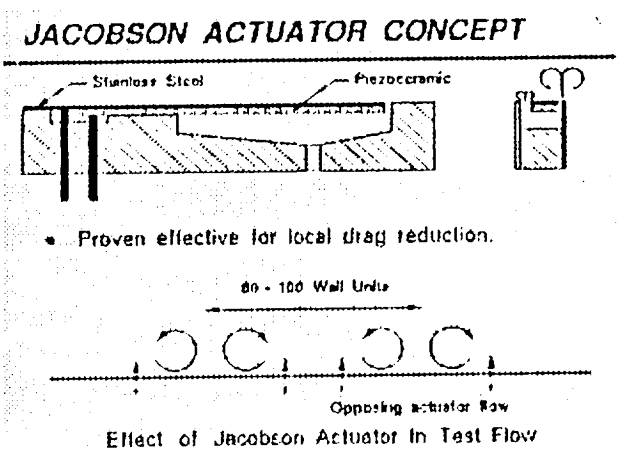


Figure 5. Jacobson actuator creates localized jets using a vibrating cantilevered beam. From W. Reynolds and S. Jacobson, Stanford University.

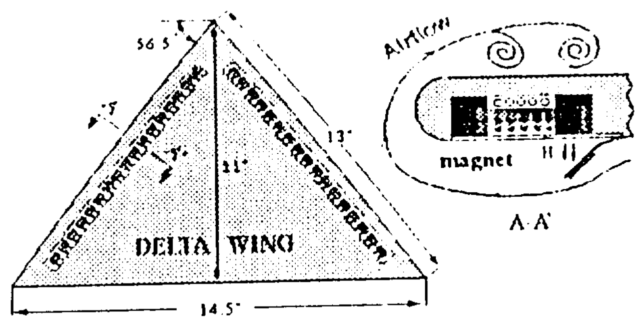


Figure 6. MEMS actuators applied near leading edge of delta wing. From C-M Ho and D. Miu, UCLA, and Y-C Tai, Caltech.